AD-785 649

DESIGN OF MAGNETIC SENSORS FOR OBTAINING AN ENVIRONMENTAL SAFETY SIGNATURE

Herbert A. Leupold, et al

Army Electronics Technology and Devices Laboratory

Prepared for:

Harry Diamond Laboratories

1974

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

DESIGN OF MAGNETIC SENSORS FOR OBTAINING AN ENVIRONMENTAL SAFETY SIGNATURE

HERBERT A. LEUPOLD, PhD, FREDERICK ROTHWARF, PhD
CARL J. CAMPAGNOULO, PhD†, JONATHAN E. FINE, Mr.†, HENRY LEE, Mr.†
USA Electronics Technology and Devices Laboratory (ECOM)
Fort Monmouth, New Jersey 07703

† Harry Diamond Laboratories, Washington, D.C.

INTRODUCTION

The safing and arming systems of most artillery projectiles in common use have a signature provided by setback forces arising from the acceleration of the projectile upon firing. To obviate the possibility of accidental arming through dropping or jolting of a round, a second signature is desirable. In projectiles fired from rifled guns the spin imparted by the rifling supplies a centrifugal force that acts as the second signature to complete the fuze arming cycle. However, in fin-stabilized rounds, since spin is absent, another means must be found for supplying the second arming signature. To obtain such a signature it was decided to employ two magnetic transducers positioned near the surface of the projectile. These transducers sense a change in magnetic flux when the projectile leaves the permeable gun barrel, and emit an electrical pulse that activates a piston motor in the arming mechanism which in turn completes the arming process.

The magnetic transducers consist of an Alnico 5 ring magnet, a magnetic keeper and a coil arranged as shown in Fig. 1. It is the flux change in the center post of the keeper upon the egress of the missile from the gun that induces the voltage pulse in the circumscribed coil. To optimize the voltage pulse with respect to magnetic material and transducer geometry, both theoretical and experimental studies were undertaken. The experiments were performed at HDL, Washington, D.C., while the theoretical work was done at USAET&DL (ECOM), Fort Monmouth, New Jersey.

OCT 4, 1974

EMPIRICAL STUDIES

The experimental studies are of two basic types. One is the field test in which the transducer is actually mounted in a shell and fired from an 81-mm mortar or a 75-mm pack howitzer. The voltage pulse generated during the transducer's egress from the muzzle is then measured using the technique described in detail by Morrow.[1] This system allows information to be transmitted from the moving projectile via a retrievable wire cable that is stored in a hollow collector cone cavity in the projectile. The wires are stretched from the transducer through the retrieval equipment to a cage mounted on the muzzle of the weapon (Fig. 2). The cage positions the bare wire in the center of the barrel and extends the necessary distance past the muzzle. Two or more wires can be used to obtain muzzle velocity as well as the pulse voltage. The wires from the cage are connected to tape recording equipment where the information is stored. A typical pulse shape thus obtained is shown in Fig. 3.

To eliminate the time, expense and relative inconvenience of the field tests, the second type of experiment was devised in which the exit of the transducer from the gun is simulated in the laboratory by means of the arrangement pictorially and schematically illustrated in Figs. 4 and 5, respectively. The transducer is placed adjacent to a rotating steel blade driven by an air turbine whose rotational velocity can be preset by adjusting a pressure regulator that controls the driving air stream. The distance of the magnetic pole pieces from the blade can be varied by means of a micrometer screw in the mounting fixture. The rotational frequency of the blade is monitored by an electronic counter.

As the blade sweeps by the transducer, two electric pulses are generated, a positive one as the leading edge of the blade passes over the transducer and then a negative one when the trailing edge sweeps by. It is the latter pulse that simulates the one obtained by the transducer leaving the gun muzzle in an actual firing. Figure 6 shows a typical oscillograph trace of the pulse obtained for a blade velocity of 420 ft/sec at a distance L_g above the transducer. Note that the pulse shape is nearly triangular with the triangle base essentially equal to the time taken for the blade edge to completely traverse the transducer. The peak voltages of pulses obtained with L_g=.150" are plotted against blade velocity in Fig. 7 where they are compared with a similar plot obtained from actual firing. The data for the two investigations agree to within experimental scatter and indicate a linear dependence of pulse height on velocity.

THEORETICAL ANALYSIS

To facilitate the choice of the design parameters, a theoretical study was undertaken to devise a method by which open circuit voltage output could be calculated from the transducer geometry and the muzzle velocity. To accomplish this, one must find the flux linking the coil for both the in-gun Φ_i and out-of-gun Φ_o situations. The mean voltage produced would then be given by

$$\bar{V} = 10^{-8} N \frac{\Delta\Phi}{\Delta t} = 10^{-8} N \frac{(\Phi_i - \Phi_o)}{D/v} \qquad (1)$$

where Δt is the time of transit of the transducer past the muzzle, D is the diameter of the transducer, v is the muzzle velocity, and N is the number of turns in the coil. As shown in Figs. 3 and 6, the pulses are nearly triangular, and so the peak voltage V_p is simply double the mean voltage $\bar{V}$.

The magnetic configuration is too complex to effect an exact solution for Φ_i and Φ_o, but a good approximation is attainable by means of the magnetic analogue to electric circuit theory. In this analogue the magnetic flux Φ, the permeance P, the magnetic scalar potential U and the magnetomotive force $F = \Delta U$, respectively, replace the usual electrical quantities current i, conductance G, electrical potential V and electromotive force $\mathcal{E} = \Delta V$. The space around the magnetic assembly is then divided into flux paths whose boundaries are defined by circular arcs and straight lines as illustrated in Fig. 8.

The effective permeances of the paths in the out-of-gun mode must then be calculated and combined to obtain the total effective permeance P_t. The load line for the configuration can then be obtained from the relation $(B/H) = (L/A)P_t$, where L and A are respectively the length and cross-sectional area of the magnet. From the point of intersection of the load line and the demagnetization curve of the magnetic material in question (Fig. 9), one can then obtain the average value B_m of the flux density in the magnet. Multiplication of B_m by A then gives Φ_t, the total flux emanating from the magnet. From the permeances of the individual paths together with Φ_t and P_t, one can calculate the fluxes in each path, just as the current in each branch of an electrical circuit can be calculated from the branch conductances, the total current and total input conductance. The magnetic case is more difficult because the permeance paths are not as clearly defined as the branches in an electrical circuit, and their boundaries must be determined by criteria discussed by Leupold et al[2] and by Roters.[3] Some of the permeance paths are of standard form and their permeances easily calculated from formulae

listed in the literature. Other permeances associated with path forms peculiar to this configuration must be derived from first principles.[2]

Calculation of the flux linkage of the sensing coil when the transducer is inside the gun is complicated by the fact that the permeances between the transducer and the gun wall are not of standard form. This problem was solved by noting that if the gun barrel can be considered as a semi-infinite extension of an infinitely permeable medium, the permeances are the same as those that would exist if the medium were replaced by the mirror image of the transducer in the medium (Fig. 8). The permeances would then be of standard form and easily calculated. Since the gun barrel is sufficiently thick to carry all flux lines reaching it from the magnet without saturating, and since the permeability of the barrel steel is orders of magnitude greater than that of free space, the assumption of equivalence of the gun barrel to a semi-infinite medium of effectively infinite permeability is justified.

The load line can then be calculated with a procedure similar to that used for the out-of-gun regime. B_m is then determined from the intersection of the load line and the recoil line for the magnet material having its origin at the point where the out-of-gun load line passes through the demagnetization curve (Fig. 9). From the value of B_m thus obtained, Φ_t can then be calculated, which together with the permeances and the help of the electric current analogue yields Φ_i. Substitution of the values of Φ_i and Φ_o in Eq. (1) gives the open circuit voltage for any given velocity.

As can be seen in Fig. 7, a comparison of the theoretical voltage vs velocity curves for magnet-to-gun gaps of .125" and .150" with those obtained from field and laboratory tests shows excellent agreement.

As a further test of the general analysis outlined above, the open-circuit voltage for a different untried configuration was predicted. This new configuration was constructed, tested in the laboratory, and the results were compared with the predicted voltage curve. As is shown in Fig. 10, agreement is as good as for the original configuration, but the voltage outputs for the alternate design are so much lower that it was not considered further.

Calculations were also made to determine the relative performance of the transducer when Co_5Sm is substituted for Alnico 5. One would expect such a substitution to be especially propitious when the system operates on load lines with values of $B/H < 7$ for which Co_5Sm has

a much larger flux density than Alnico 5 (Fig. 9), and hence gives rise to a greater $\Delta\Phi$. However, as the load line slopes become greater than about 10, Co_5Sm gradually loses this advantage to Alnico 5 (Fig. 9). Even between slopes of 10 and 12 where the Co_5Sm still enjoys a slight superiority in this regard, the greater slope of the Alnico 5 recoil line (4.3 as compared to 1.0 for Co_5Sm) enables it to produce a greater $\Delta\Phi$ in the transducer center post. The calculations bear out these expectations in that for the standard design for which B/H varies from 5 to 7, they predict a 50% larger voltage pulse for Co_5Sm than for Alnico 5. For the less efficient coplanar design of Fig. 10, where the load line slopes are 10.4 and 11.5, the predicted outputs are almost the same, with a small advantage in favor of Alnico 5.

In the foregoing calculations we have divided the problem into permeance paths on a relatively gross scale from which one can expect only approximate results. In principle, it is possible to subdivide the magnet and environment into a grid work of square permeance paths. Since the magnet has cylindrical symmetry, this reduces to an essentially two-dimensional problem. This array of squares can then be considered as a network of Maxwellian current loops to which one can apply the magnetic analogues to Ohm's law, Kirchhoff's law, and all the other techniques commonly employed in solving electrical network problems. If the loop contains magnetic material, it is analogous to an electrical loop containing a current source with the pole strength acting as the analogue to the current supplied by the electrical source. The more finely one spaces the grid, the more precise will be the solution, with an infinitesimal grid spacing yielding the exact solution. Solving for an infinitesimal grid is tantamount to a boundary-value solution of Maxwell's equation, which is possible for only the simplest geometries. Even for a grid of n loops, n simultaneous equations must be solved, and to obtain reasonably accurate results for most problems, n must be made too large for a solution to be practicable without the aid of a large computer. Such an approach has been developed by Harrold[4] for geometries having cylindrical symmetry.

Computer plots of flux lines were made for the standard HDL configuration with a .125" spacing from the gun barrel and for the out-of-gun mode. These are illustrated in Fig. 11, where one half of the inverted transducer is shown. Note the general resemblance to the conventionalized permeance paths of Fig. 8, and also the remarkable agreement in geometric detail between the computer plot and the rough permeance calculations. Point A is the point which, according to the long-hand calculations, is the demarcation between the flux lines that go from limb to wall and those that return back to the other end of the limb. Point B is the calculated effective equator of the magnet;

note that it is the approximate symmetry center for the P_O flux lines. Point C is the calculated point that marks the switching of the center post flux lines from the permeable wall to the ring magnet. Point D is the predicted switchover point from P_r paths to P_B paths.

SYSTEM CONSIDERATIONS

For the transducer design to be incorporated into an arming system, special circuitry needed development in order to fire the explosive motor in the safing-arming chain. The output requirement for the generator is determined by the energy to activate the piston motor (500 ergs) and to power the electronic circuit.[5] To insure uniform performance over the entire velocity range (300-3000 feet per second), the energy carried by the triangular transducer pulses is stored in a capacitor. The optimum value for the capacitance was determined by a computer program which simulated triangular transducer pulses of magnitudes corresponding to the various velocities of egress. The program then calculated the energy outputs for various capacitance values inserted into the arming circuit. The optimum capacitance was not critical and lay between 2 and 4 µF. For such a capacitor the energy transfer to the arming mechanism was almost constant at .02 joules, which is more than sufficient to insure reliability of performance.

The 8" SALGP projectile was modified to carry two induction generators electrically in series and located 180° apart on the surface of the projectile. To activate the piston motor, signals are required at muzzle exit from both generators. This dual generator system has two distinct advantages over the use of a single generator. First, random electrical noise in one generator will not cause the piston motor to be prematurely fired as can occur with a single generator system. Balloting pulses resulting from the shell traveling in the gun tube are rejected as they are induced 180° out of phase. Second, in the single generator system, the amount of energy transferred from the generator to the storage capacitor can be low. This occurs if the projectile is side-slapped while exiting. Such a circumstance results in a large center-post-to-barrel gap on egress, and consequently, a low-energy pulse results. The dual-generator system eliminates this problem. If the projectile leaves the barrel closer to one side than the other, the generator closest to the wall will emit an increased output signal, thereby compensating for the decreased output produced by the opposite generator. Therefore, an amount of energy several times greater than needed to fire the piston motor will always be available in the storage capacitor.

An electronic logic circuit was developed in order to implement the dual generator system. This circuit fires the piston motor only when the pulses occur within a 200 μs 'window' and uses power derived solely from the output on egress of the induction generators.[5]

Successful system field tests were conducted on 10 and 11 April 1973, at the Blossom Point firing range in which a total of nine rounds were fired, four with single sensors in an 81-mm mortar and five with dual sensors in a 75-mm pack howitzer. All used low voltage, high current, 160-turn coil inductive transducers. Only the unloaded open circuit voltages of the generators were measured for the mortar rounds (shots 1-4). For the howitzer firings, shot 5 determined the open circuit voltages for each of the generators, in shots 6 and 7 the generators were each loaded with a 3.3 μF condenser, and in shots 8 and 9 the entire external fuze circuit loaded the generators. No data was obtained for shots 4 and 7 due to mechanical failure of the data retrieval cable. The results are summarized in Table I. Note the overall good agreement of the measured voltages with theoretically expected values. The only round for which there was a significant disparity was the first. The disagreement is attributed to deterioration of the measuring apparatus which had been used in previous testing. New instrumentation was employed for the remaining firings and no further major discrepancies resulted.

CONCLUSIONS

The foregoing agreement with experiment confirms the applicability of the long-hand computational method, which yields very good results in spite of many simplifications and approximations. Confidence in the technique is further bolstered by the more exact computer calculations that show its capability for predicting accurately not only flux linkages but even small quantitative details of the flux pattern surrounding the transducer.

Further, the approximate long-hand technique is applicable to a variety of configurations which lack cylindrical symmetry and hence are not easily solvable by the exact fine-grid computer methods. The formulae derived from the long-hand method can, of course, be used in a computer to predict output voltages for a variety of dimensional changes in any given configuration. The computer printout can then be cast in the form of a matrix from which the optimum design parameters can be readily deduced.

The complete system resulting from the work at HDL and ECOM has been successfully fired aboard the 8" guided projectile at the Naval Weapons Laboratory. All telemetry data from the fired rounds

have indicated that the transducer produced the voltage needed to provide the second signature to the safing and arming system. This concept will undergo engineering and development for production in Fy-75.

This work emphasizes the fruitfulness of cooperative ventures between different organizations in bringing complex design problems to a successful conclusion.

REFERENCES

1. W. T. Morrow, "A Hard Wire Technique for Extracting Data from a Projectile During In-Bore Environments," HDL-TM-72-27 (October 1972).

2. H. A. Leupold, F. Rothwarf, C. J. Campagnoulo, H. Lee, and J. E. Fine, "Magnetic Circuit Design Studies for an Inductive Sensor," TR-ECOM-4158 (October 1973).

3. H. C. Roters, Electromagnetic Devices, (John Wiley & Sons, Inc., 1941).

4. W. J. Harrold, IEEE Transactions on Magnetics, Vol. MAG-8, No. 1, p. 23, March 1972.

5. C. J. Campagnoulo, J. E. Fine, H. C. Lee, J. E. Forrest, F. Rothwarf, and H. Leupold, "Induction Sensor to Power Safing-Arming System for the Navy 8-Inch Non-spin Round," HDL Report, to be published 1974.

TABLE 1. FIELD TEST DATA

No.	Description of Generator Output	Velocity (fps)	Expected (volts)	Measured (volts)	Energy (ergs)
	81-mm Mortar Rounds				
1	Open Circuit	620	11	6.5	-
2	Open Circuit	610	11	10.8	-
3	Open Circuit	630	7	7.6	-
4	Open Circuit	1100	20	-	-
	75-mm Howitzer Rounds				
5	(a) Open Circuit	540	14	11	-
	(b) Open Circuit	540	14	11	-
6	(a) w/3.3 μF Load	540	10	9.5	1500
	(b) w/3.3 μF Load	540	10	10.4	1800
7	(a) w/3.3 μF Load	1200	11	-	-
	(b) w/3.3 μF Load	1200	11	-	-
8	w/External Fuze Circuit Load	510	9.5	8.5	1200
9	w/External Fuze Circuit Load	1100	11	10.5	1800

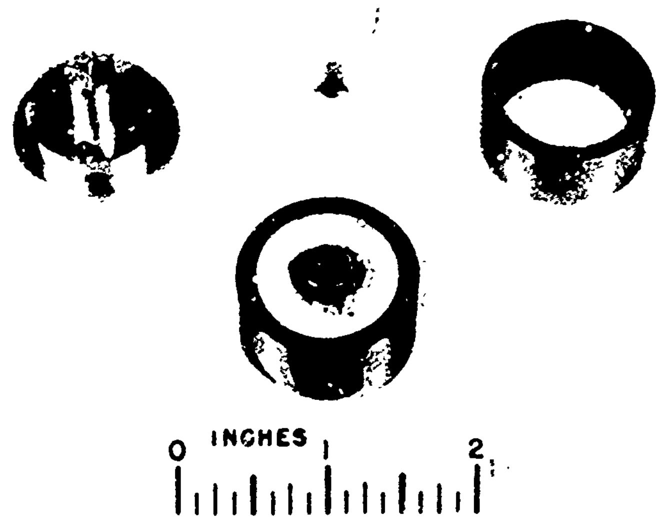


Fig. 1. Assembled induction sensor and its components

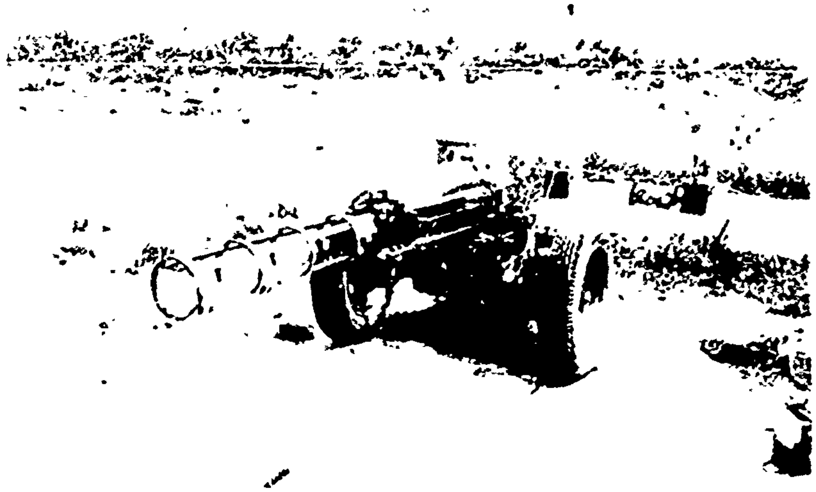


Fig. 2. Cable centering cage on 75-mm pack howitzer

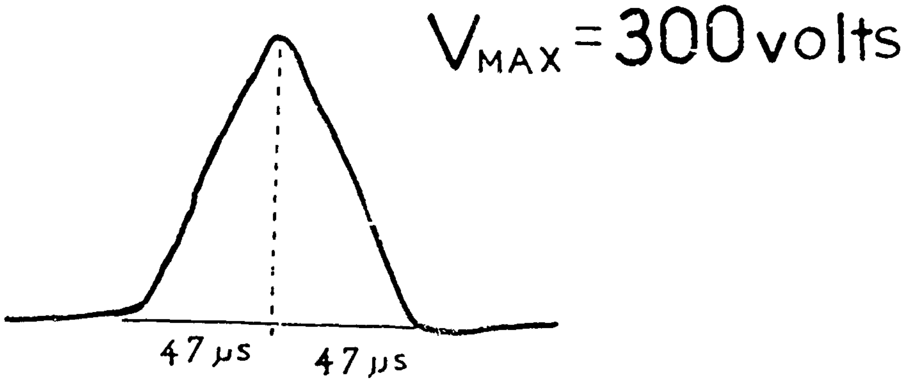


Fig. 3. Typical field test pulse

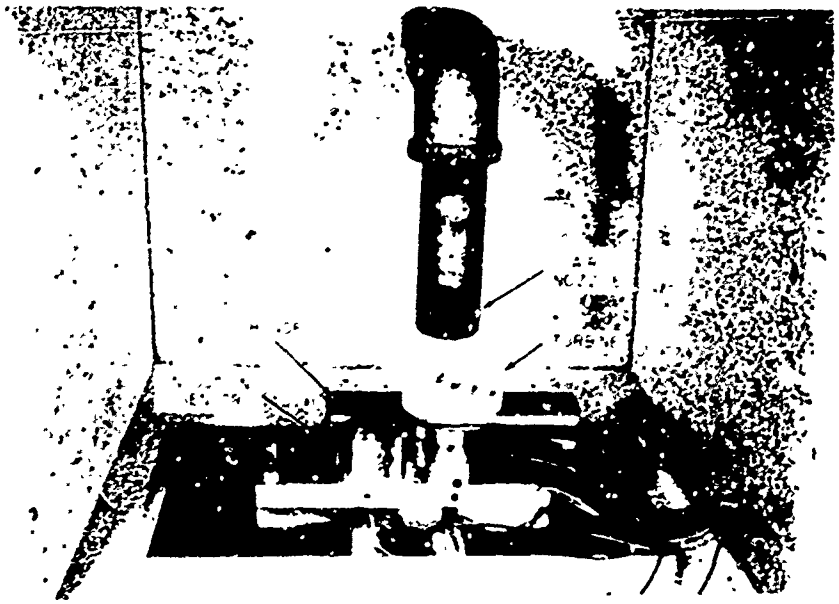
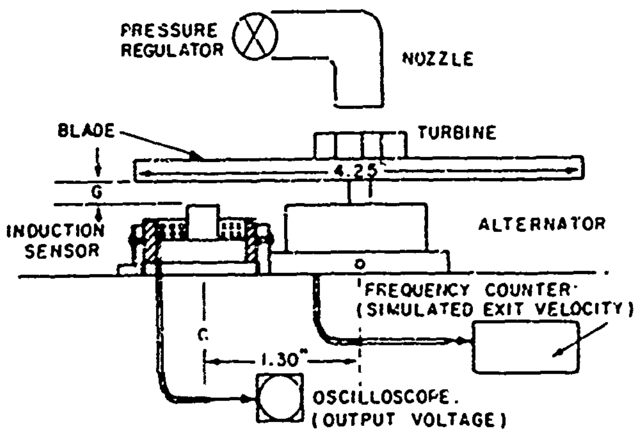


Fig. 4, Apparatus for simulation of firing test

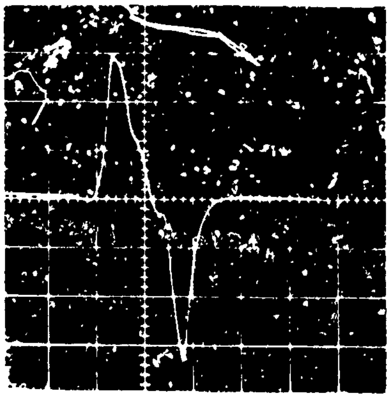


1 PRESSURE REGULATOR CONTROLS ROTATIONAL SPEED OF ALTERNATOR BLADE

2 ALTERNATOR CAN BE RAISED OR LOWERED TO OBTAIN DESIRED GAP DIMENSION, G, BETWEEN BLADE AND KEEPER POST.

3 INDUCTION SENSOR IS SEATED IN A MOUNTING FIXURE

Fig. 5. Schematic of induction sensor test apparatus



Amp = 50 V/cm
t = .2 msec/cm
Lg = .150 in.
Vel = [illegible]20 fps

Fig. 6. Voltage pulses obtained from a simulated firing test

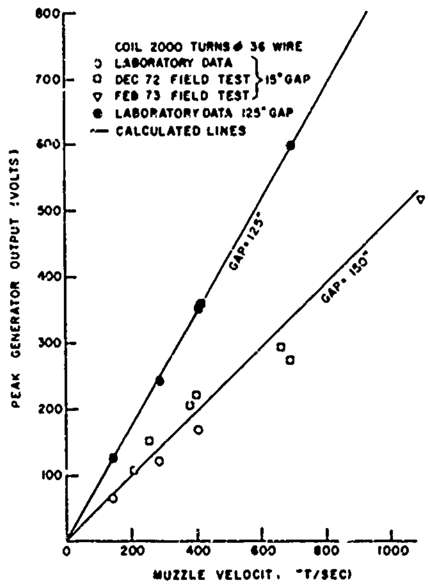
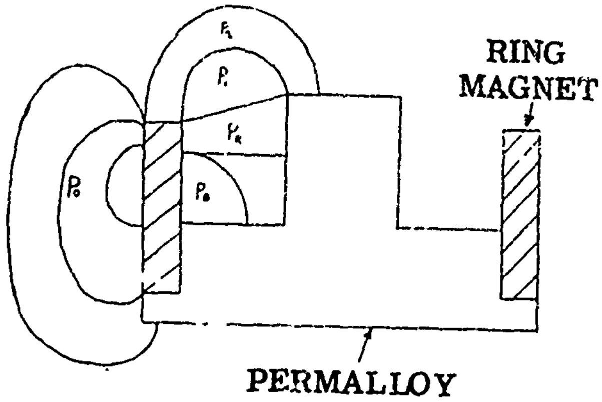
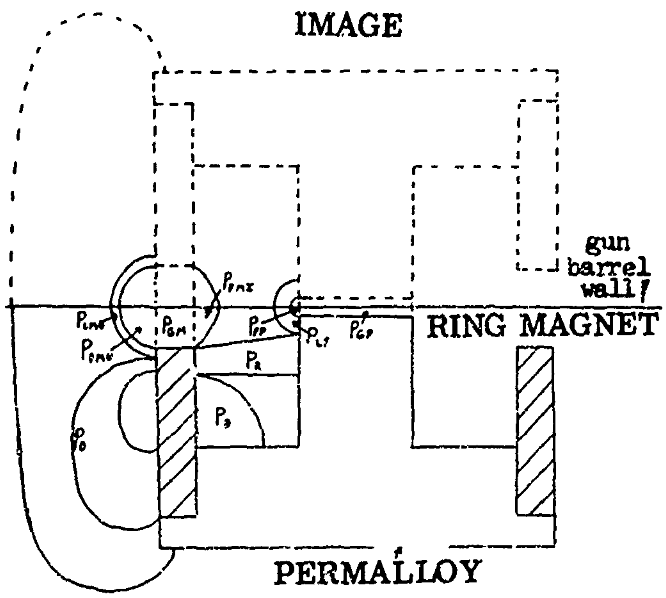


Fig. 7. Comparison of experimental with calculated peak voltages for HDL generator with a 2000-turn coil

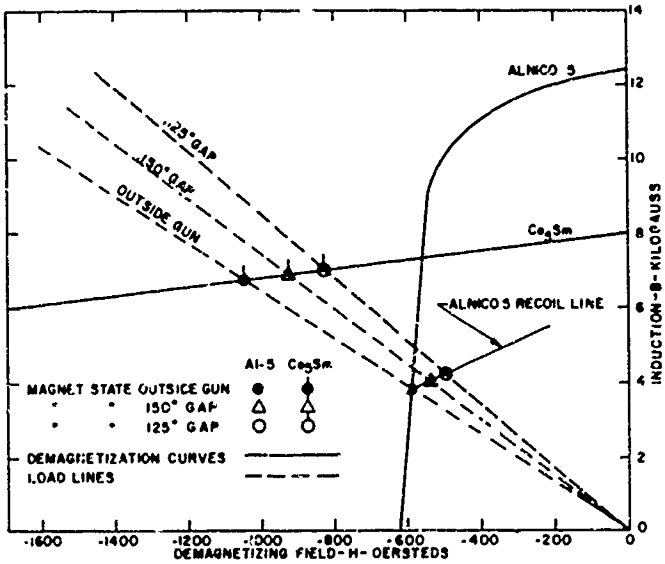


(a) outside of gun

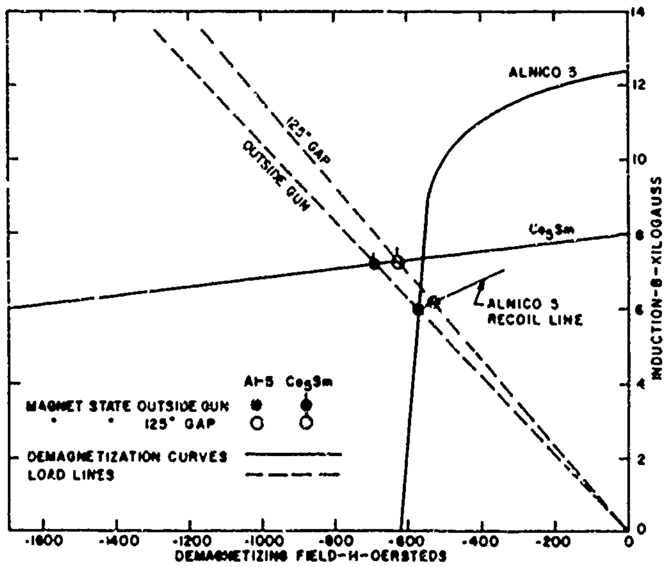


(b) inside of gun

Fig. 8. Permeance paths with transducer



DETERMINATION OF B FOR HDL TRANSDUCER



DETERMINATION OF B FOR COPLANAR TRANSDUCER

Fig. 9. Determination of B from the load lines of various configurations

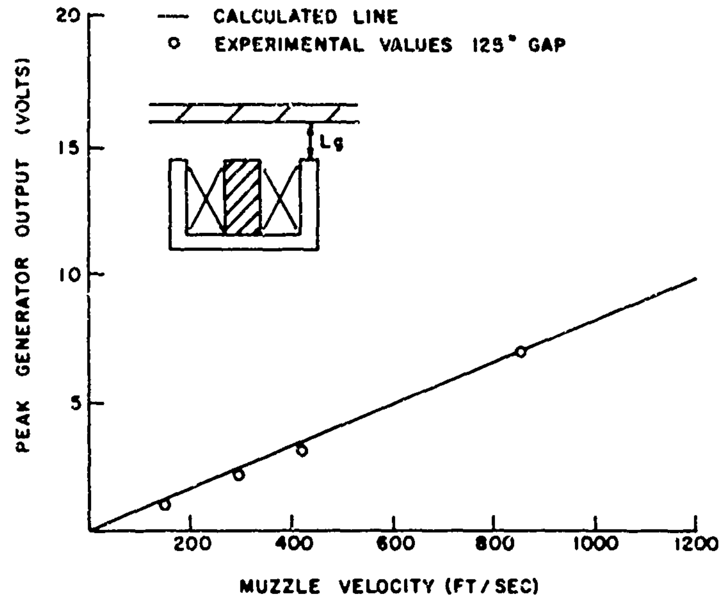


Fig. 10. Performance curve of coplanar transducer

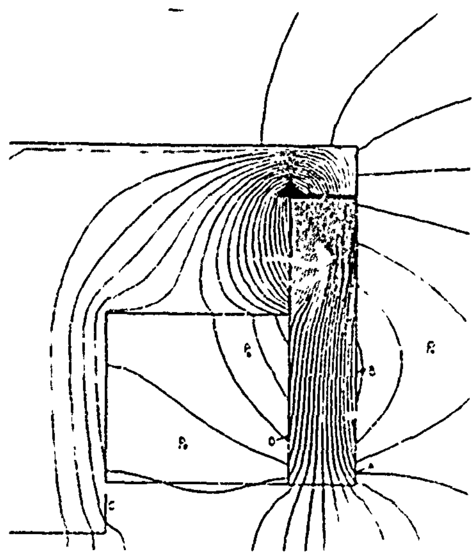


Fig. 11. Computer plot of flux lines with HDL generator in gun